High-radiance LDP Source: Clean, Reliable and Stable EUV Source for Mask Inspection

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OUTLINE

- **Basic principle and system overview**
- **Key features: spectrum, plasma size, brightness**
- **Cleanliness: debris mitigation**
- **Stability and reliability**
- **Other applications: compact source, beam line**
- **Summary**

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Laser-assisted Discharge-produced Plasma

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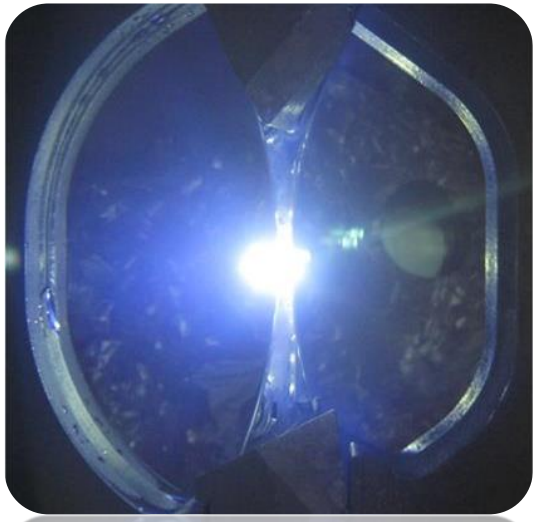
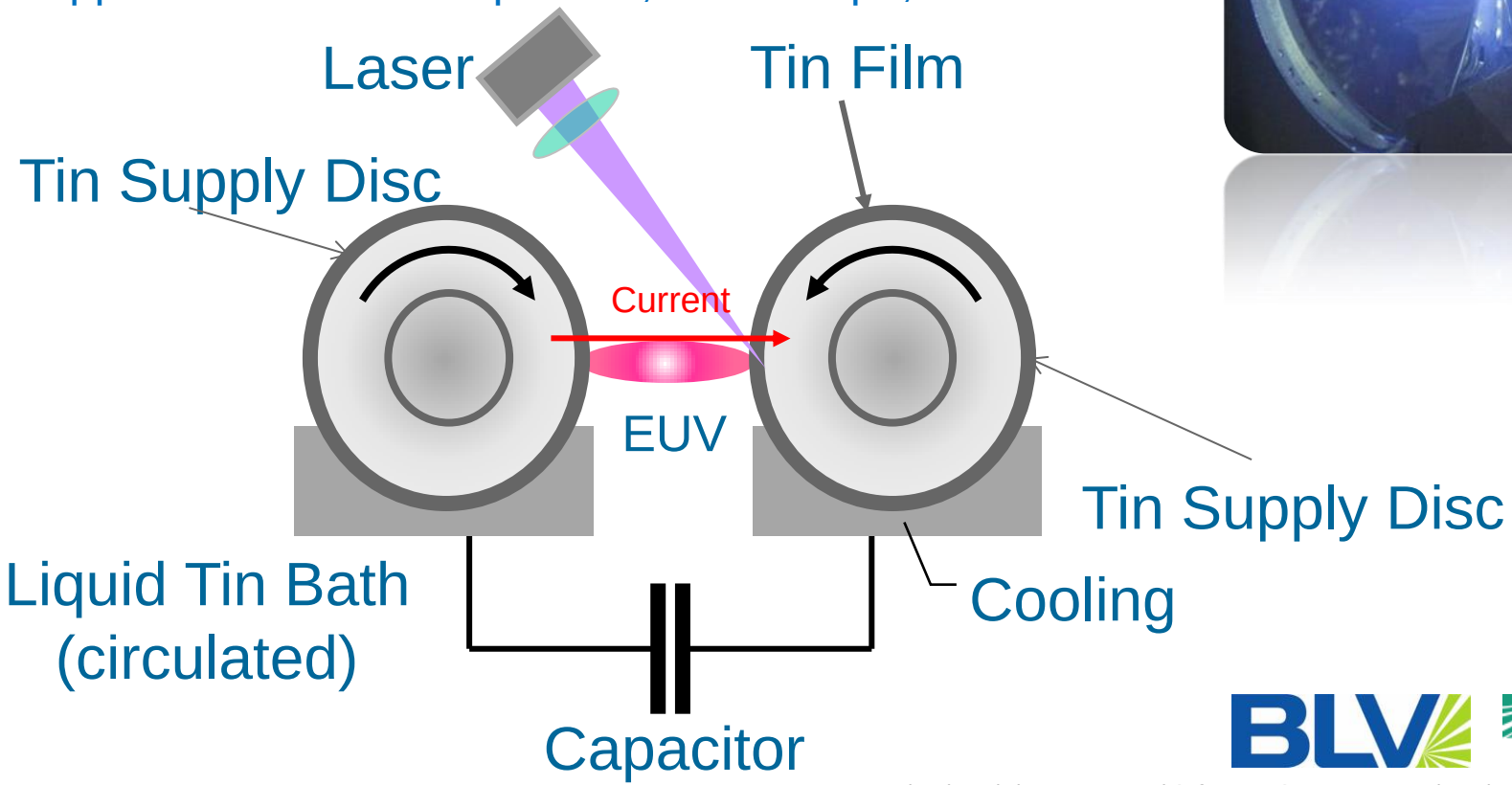
- Wavelength: 13.5 nm
- High brightness
- Appropriate plasma size (broad profile)
- Stable: no spatial and timing synchronization needed
- Reliable: 24/7 operation
- Clean: powerful debris shield
- Applications: mask inspection, microscope, etc





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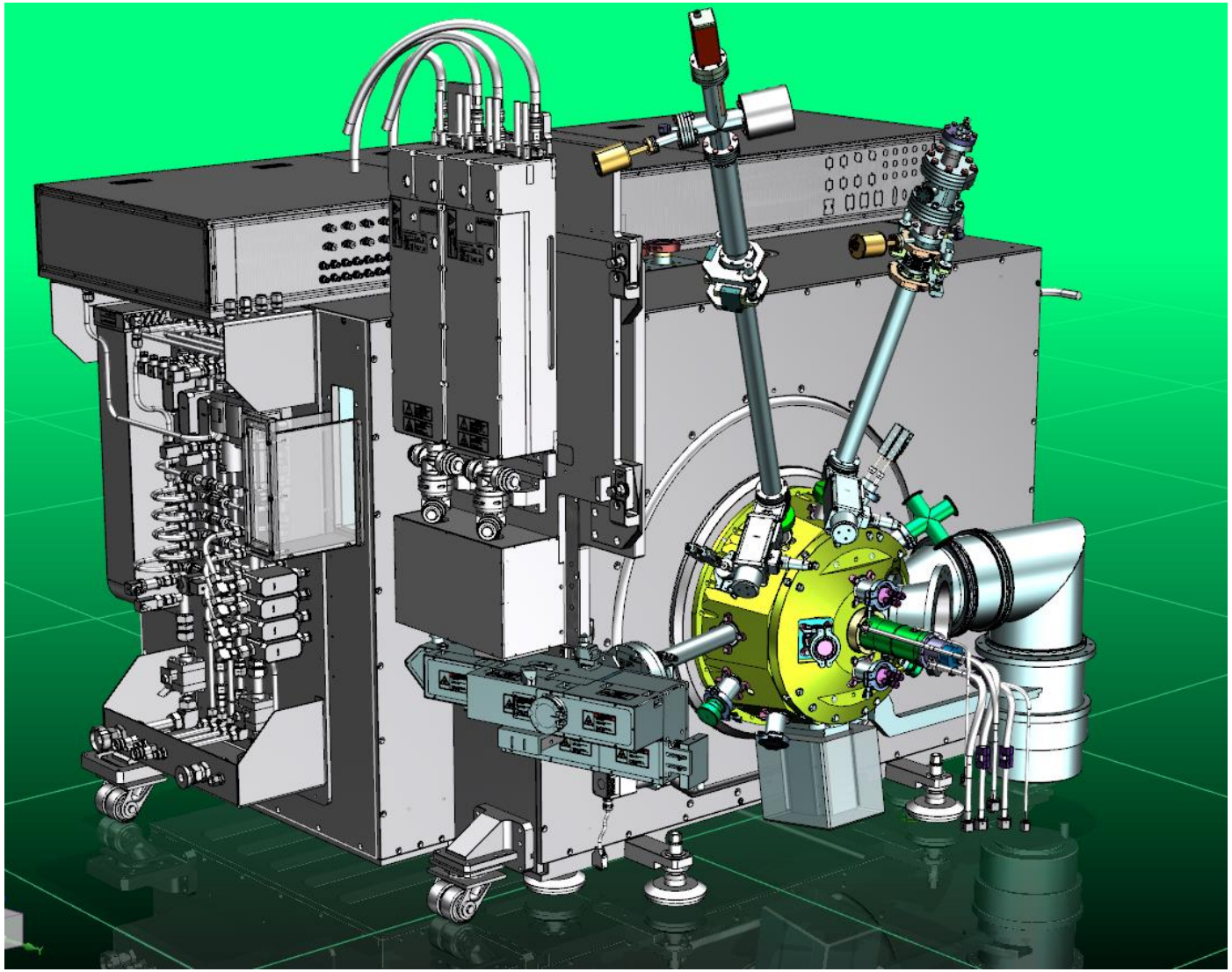
LDP machine architecture



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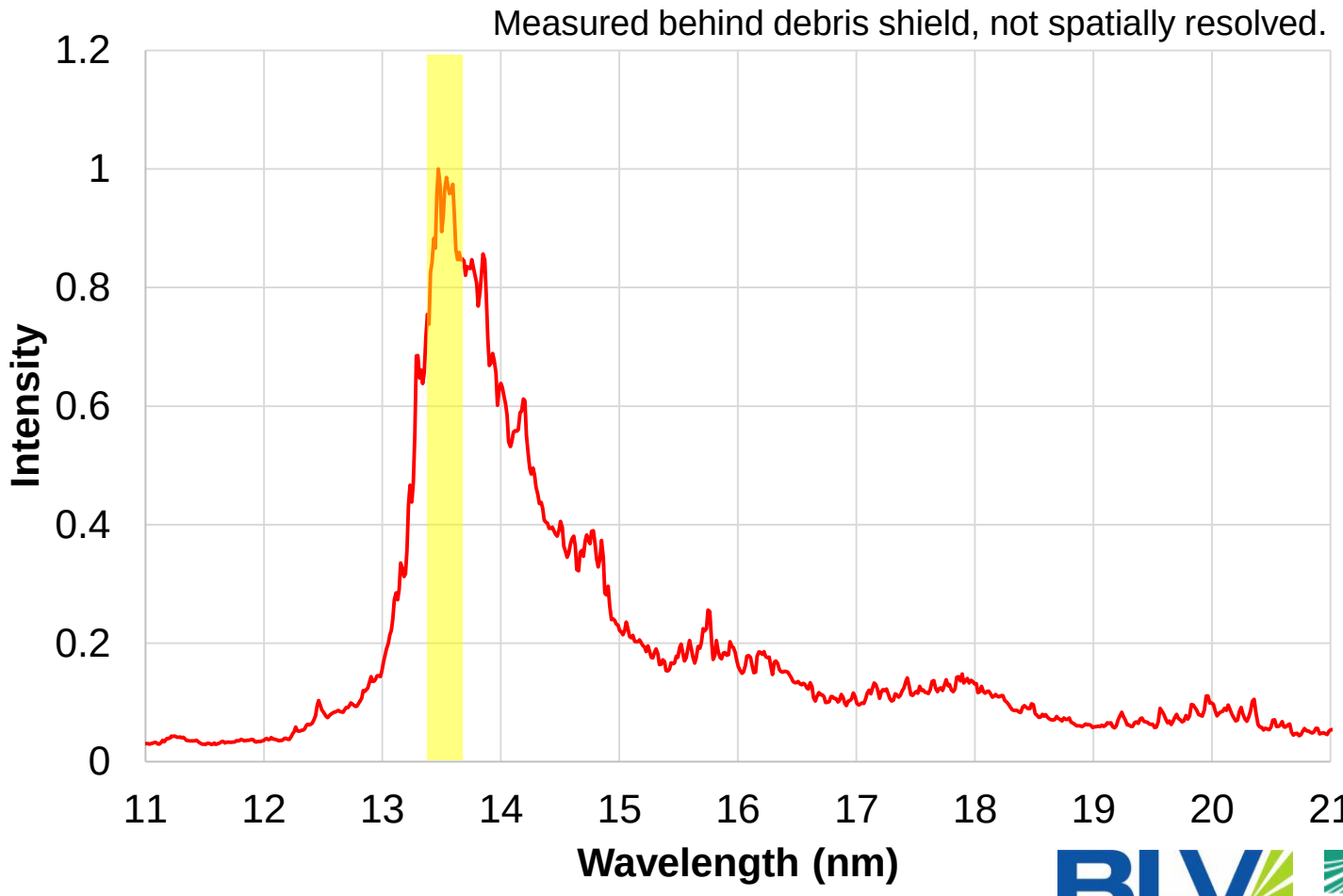
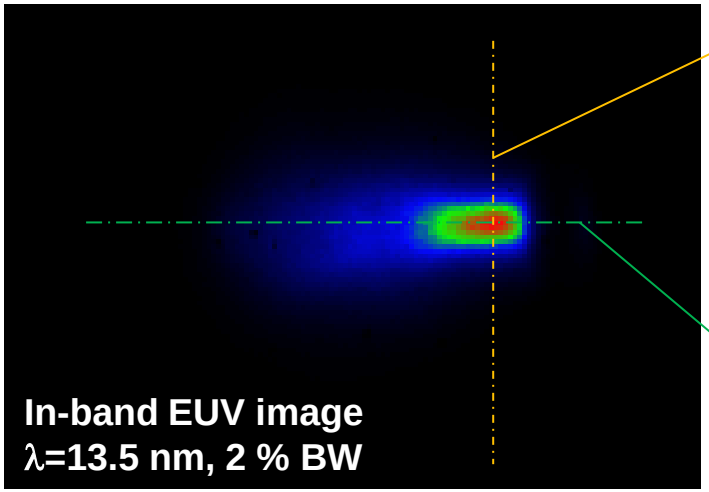
Emission spectrum: similar to CO_2 laser-driven LPP

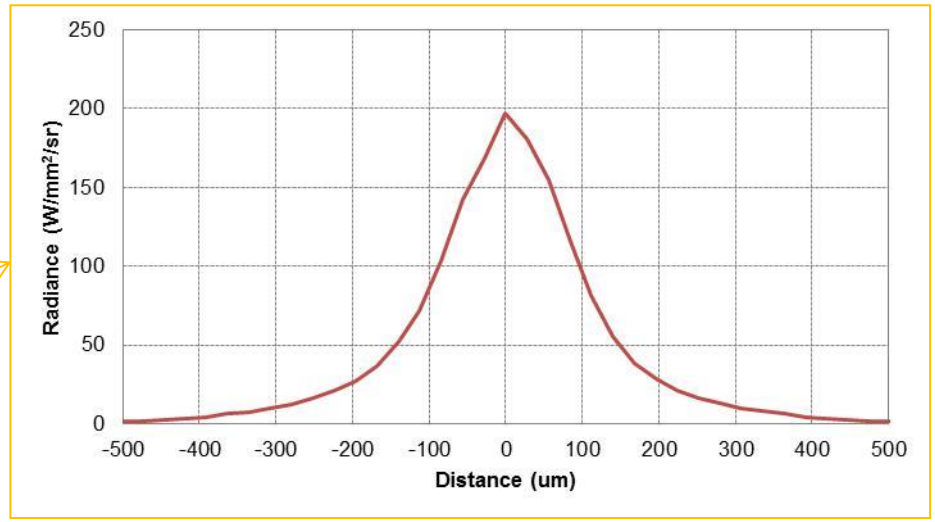
- Similar spectrum to Sn-LPP used in EUV scanner
- Beneficial in inspection and other applications



High radiance, appropriate plasma size

- High peak radiance at plasma
- Plasma size smaller than DPP, larger than LPP: good spatial stability





10 kHz, continuous operation

- Diameter: 200 μm (FWHM)
- Length: 450 μm (FWHM)

Mechanical debris shield concept

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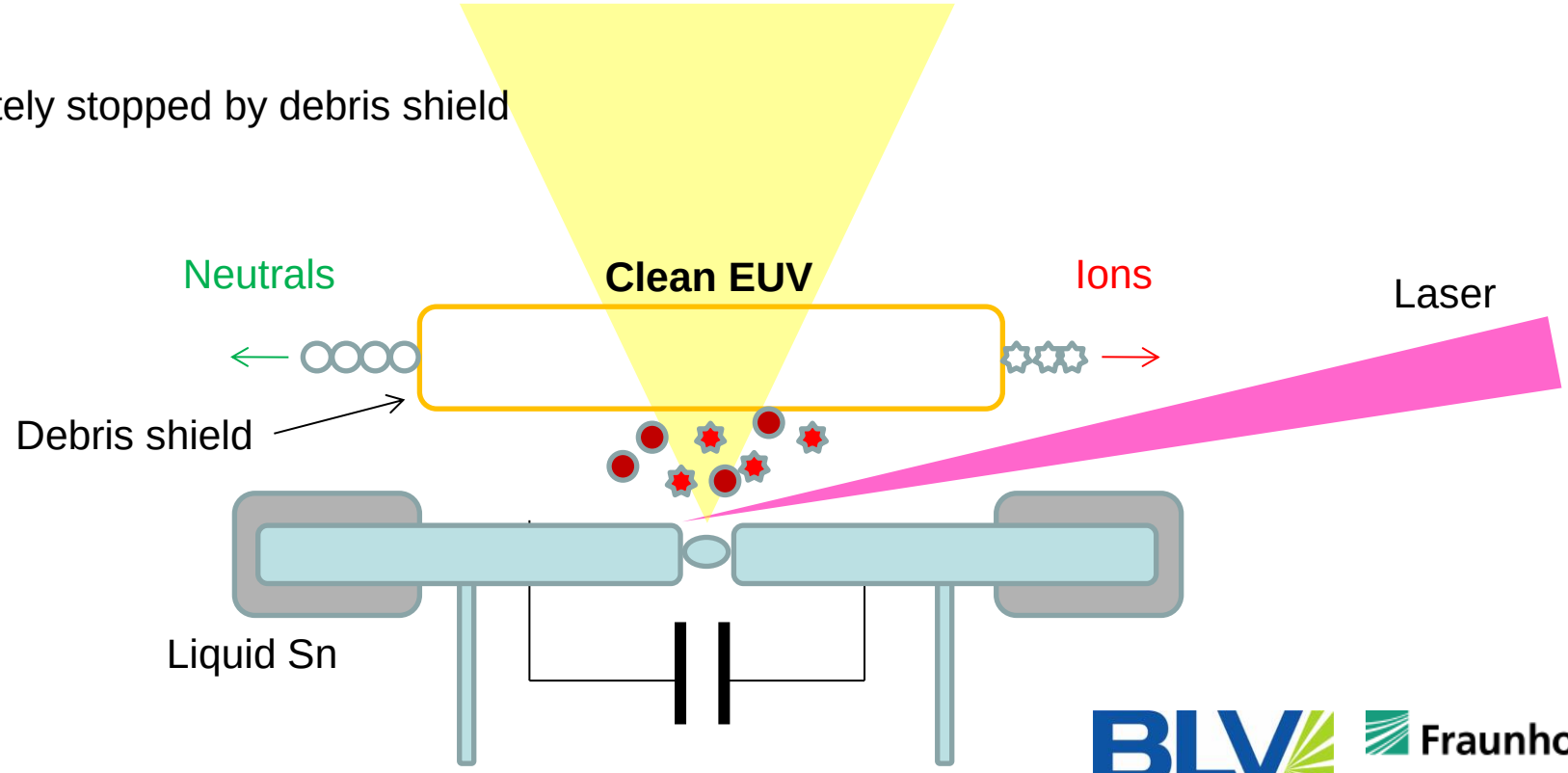
Fast ions
- Mostly stopped by debris shield
- Slow down in debris shield

Neutrals
- Completely stopped by debris shield



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Radiance behind debris shield: 145 W/mm²/sr

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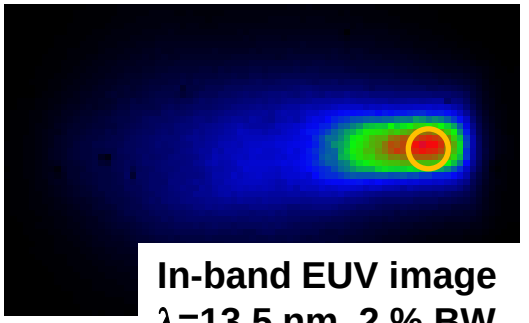
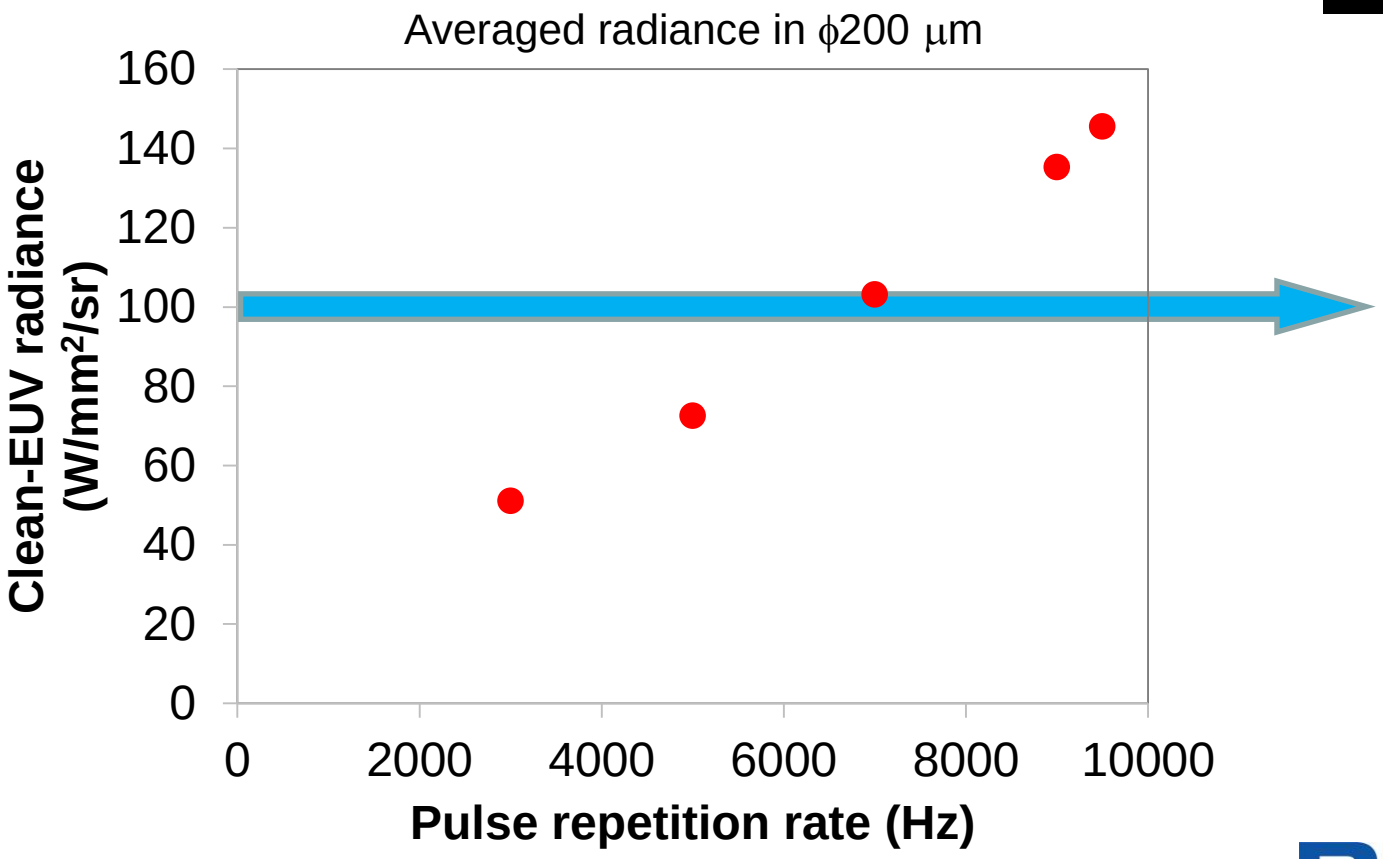
Measured behind debris shield as clean EUV photon

- Area-averaged radiance: 145 W/mm²/sr
  45 % brighter than wanted



In-band EUV image
λ=13.5 nm, 2 % BW



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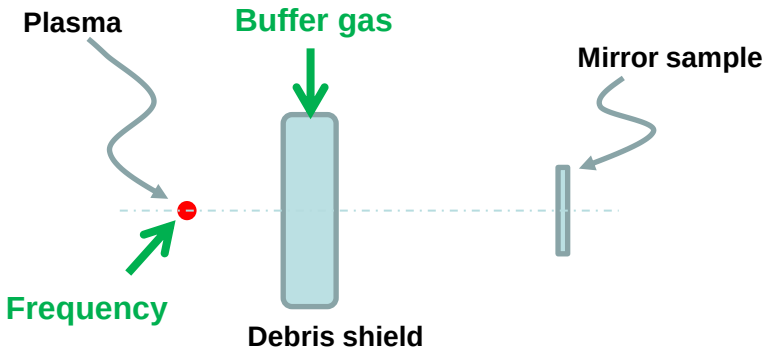
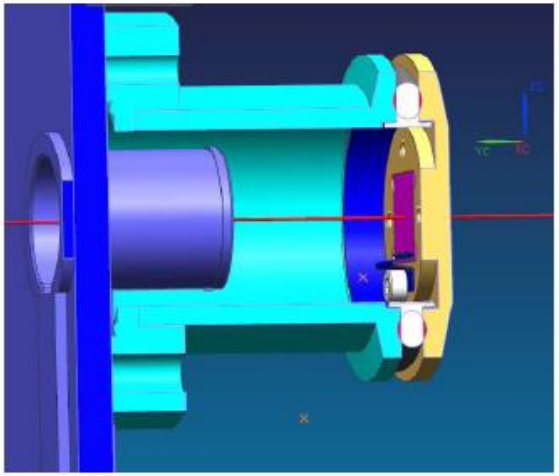
Cleanliness evaluation

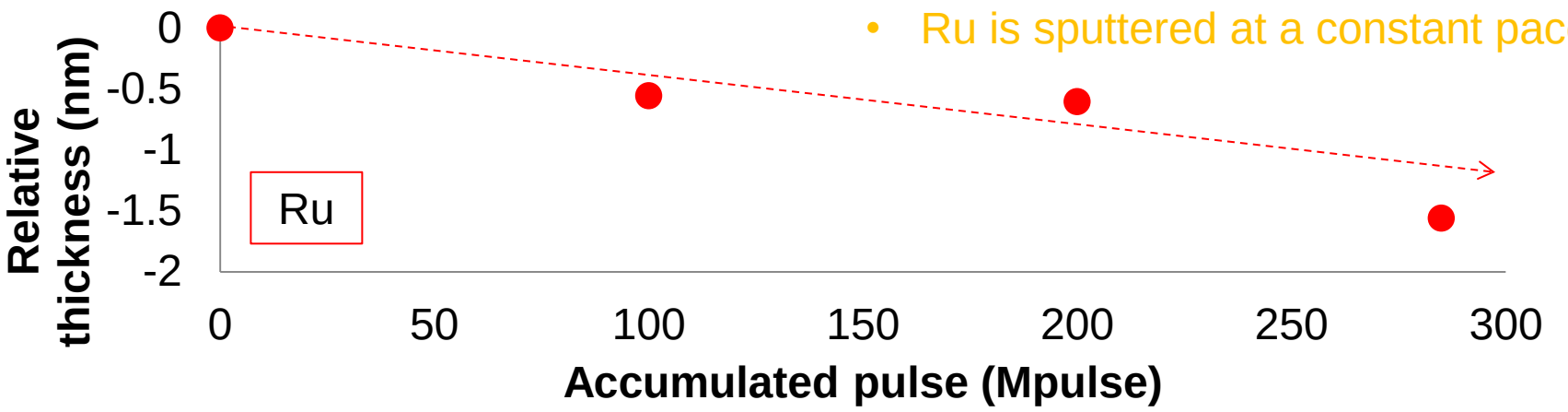


Discharge frequency:	5~9 kHz
Buffer gas:	Standard
Sample:	8-nm-thick Ru on Si Mo/Si MLM
Incidence angle:	90˚
Analysis:	XRF, TEM

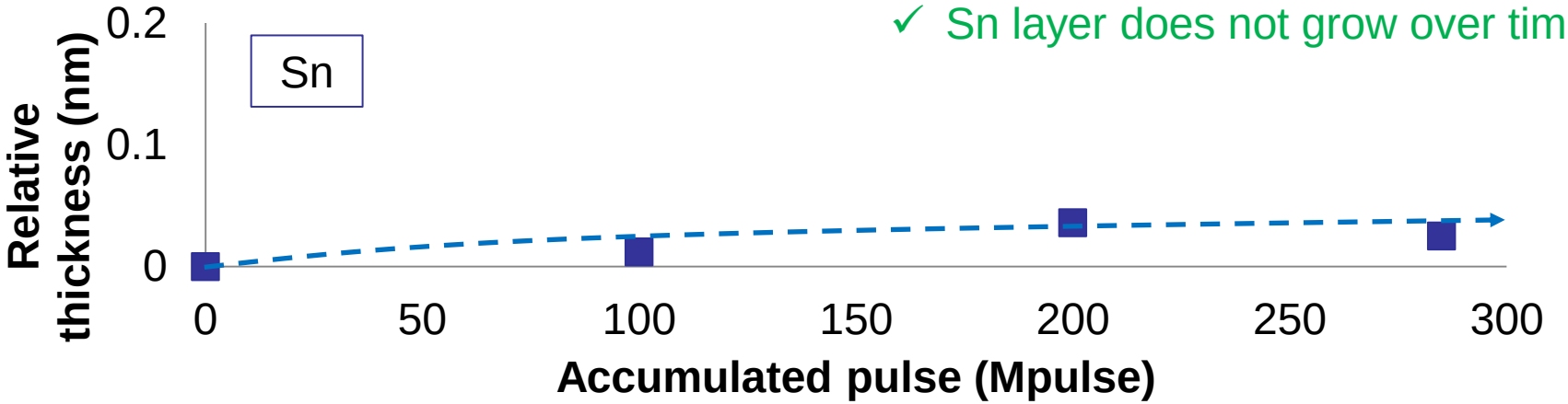
After 100~500M pulse



Cleanliness: sputter/deposition growth



- Ru is sputtered at a constant pace.

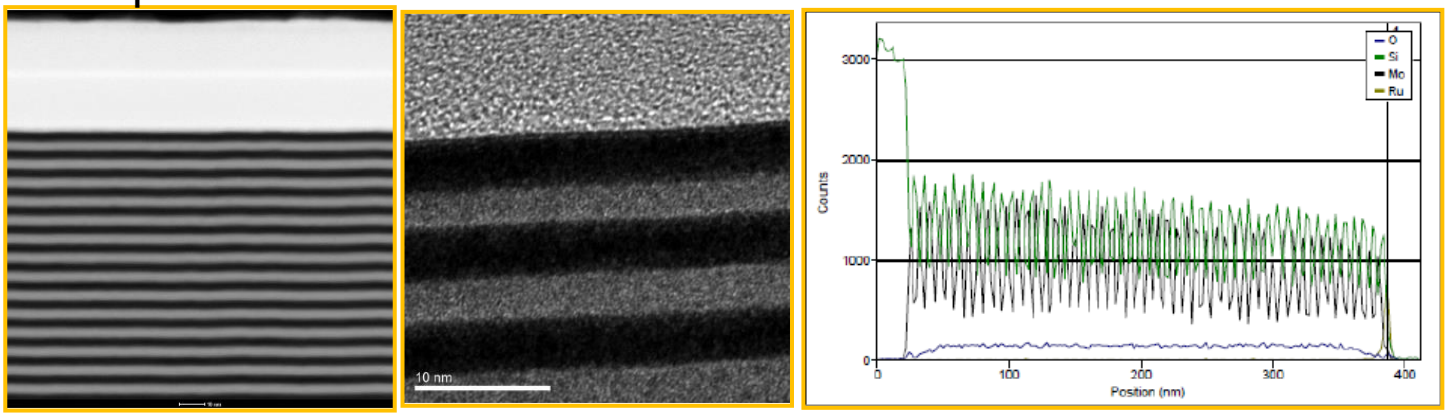


✓ Sn layer does not grow over time.

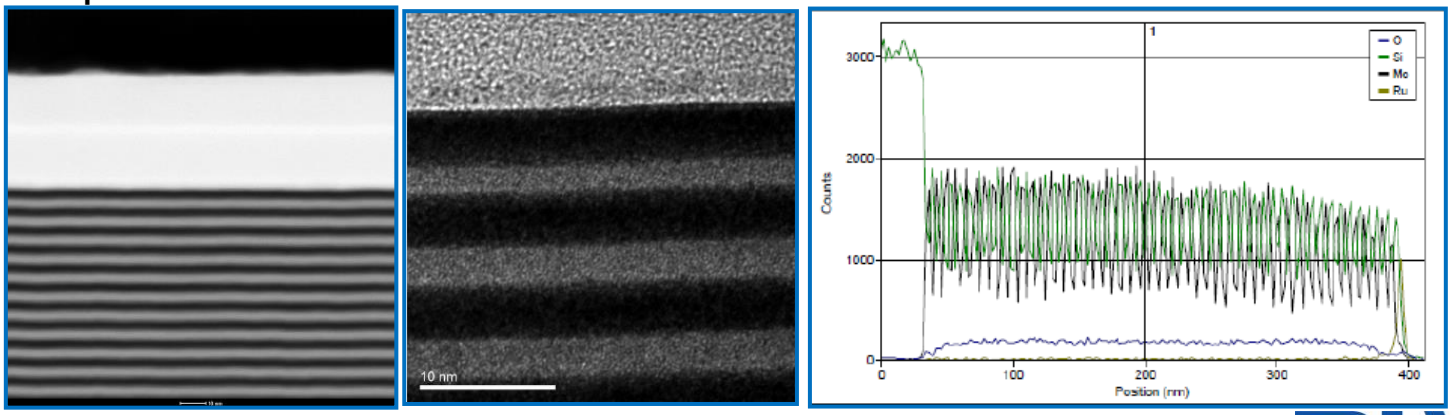
Cleanliness: Mo/Si mirror exposure

- No damage was observed on the exposed Mo/Si multilayer mirror sample after exposure.
  - ✓ No Sn deposition, No erosion, No layer distortion
  - ✓ No change in reflectivity

Unexposed area



Exposed area



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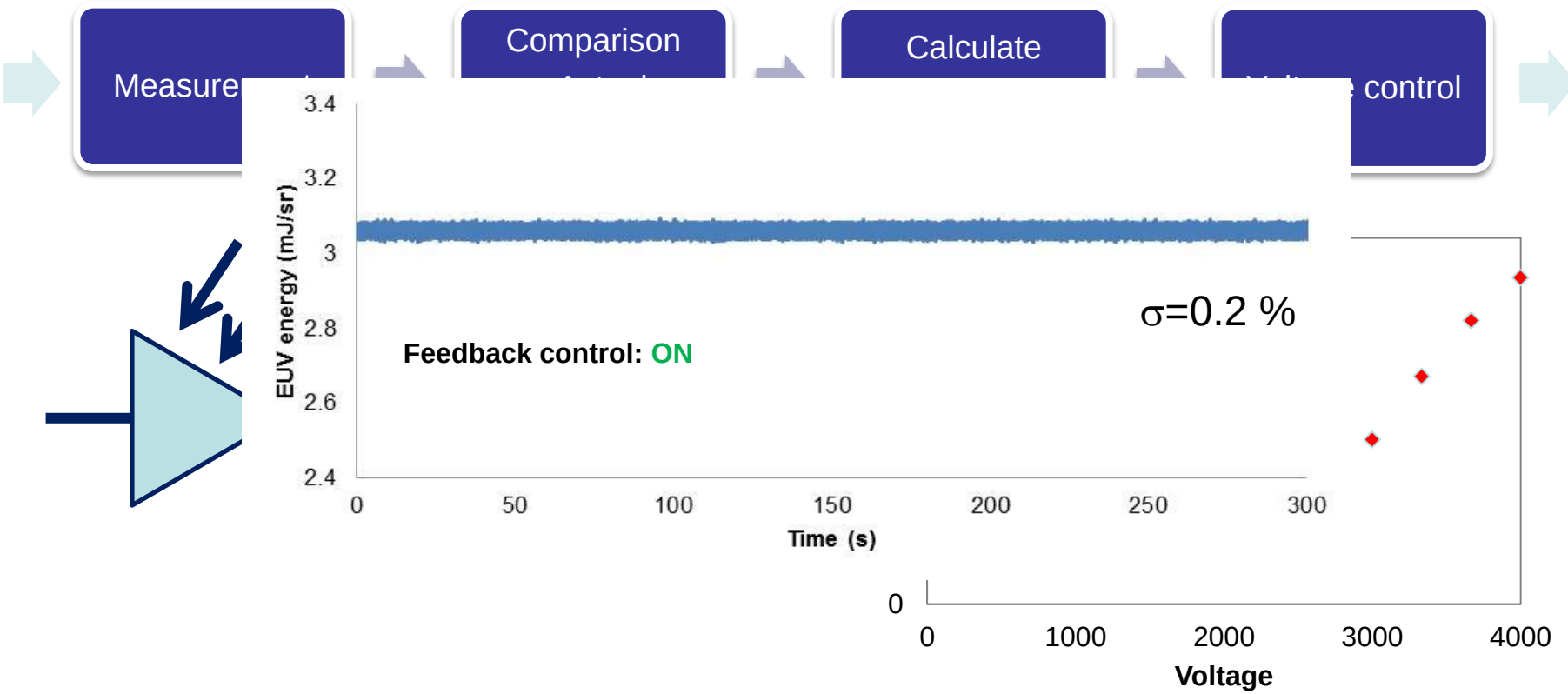
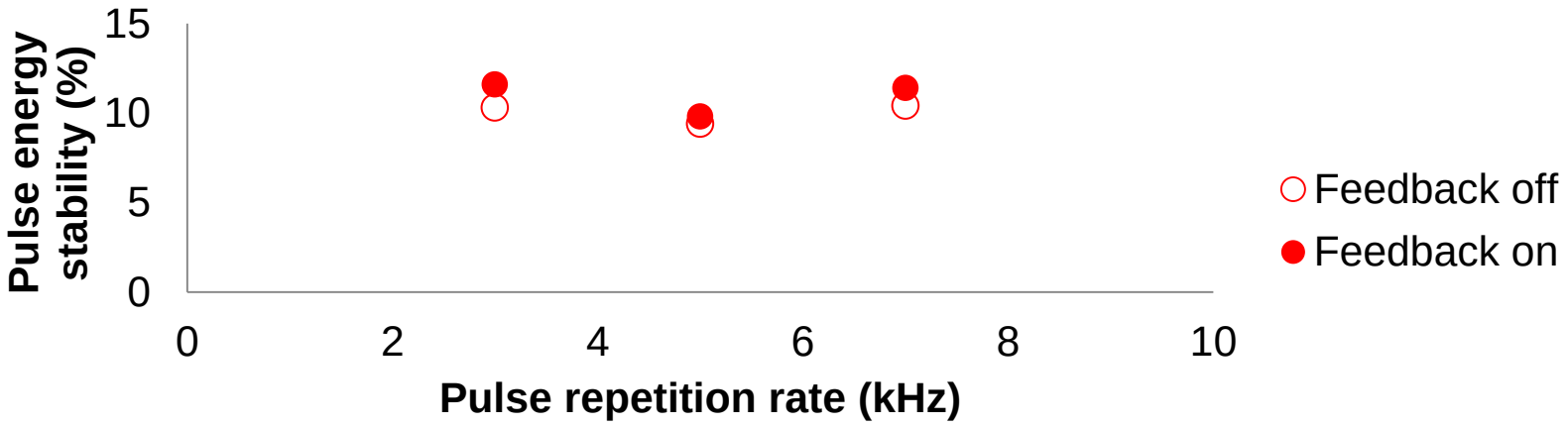
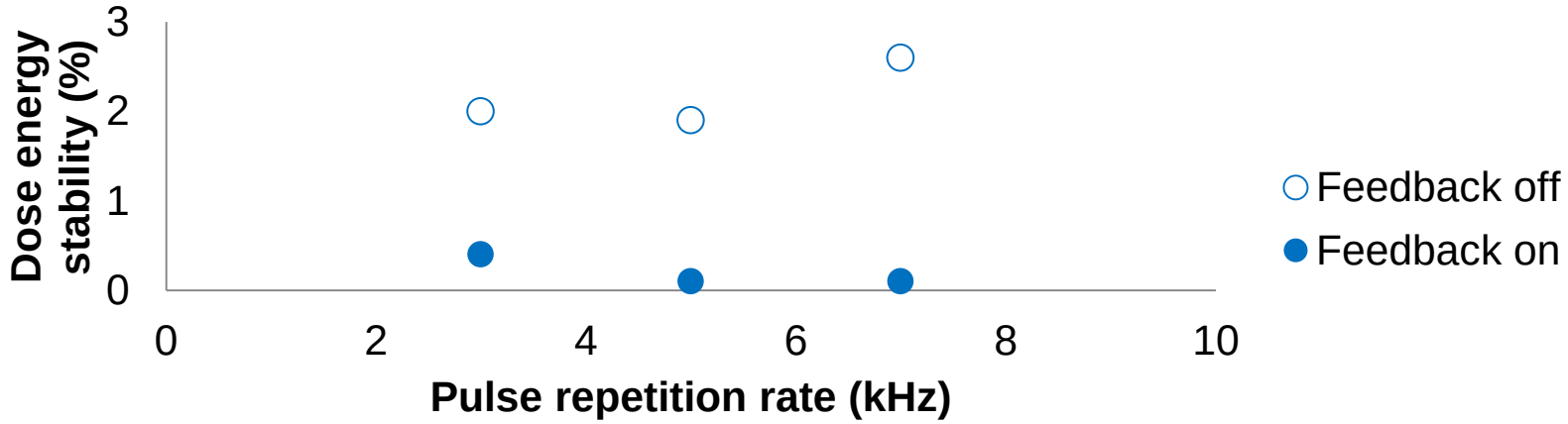
Energy stability: feedback control

- Feedback control to stabilize energy dose
- Pulse-to-pulse energy measurement and voltage control.
  - Radiance can also be used as a target value.



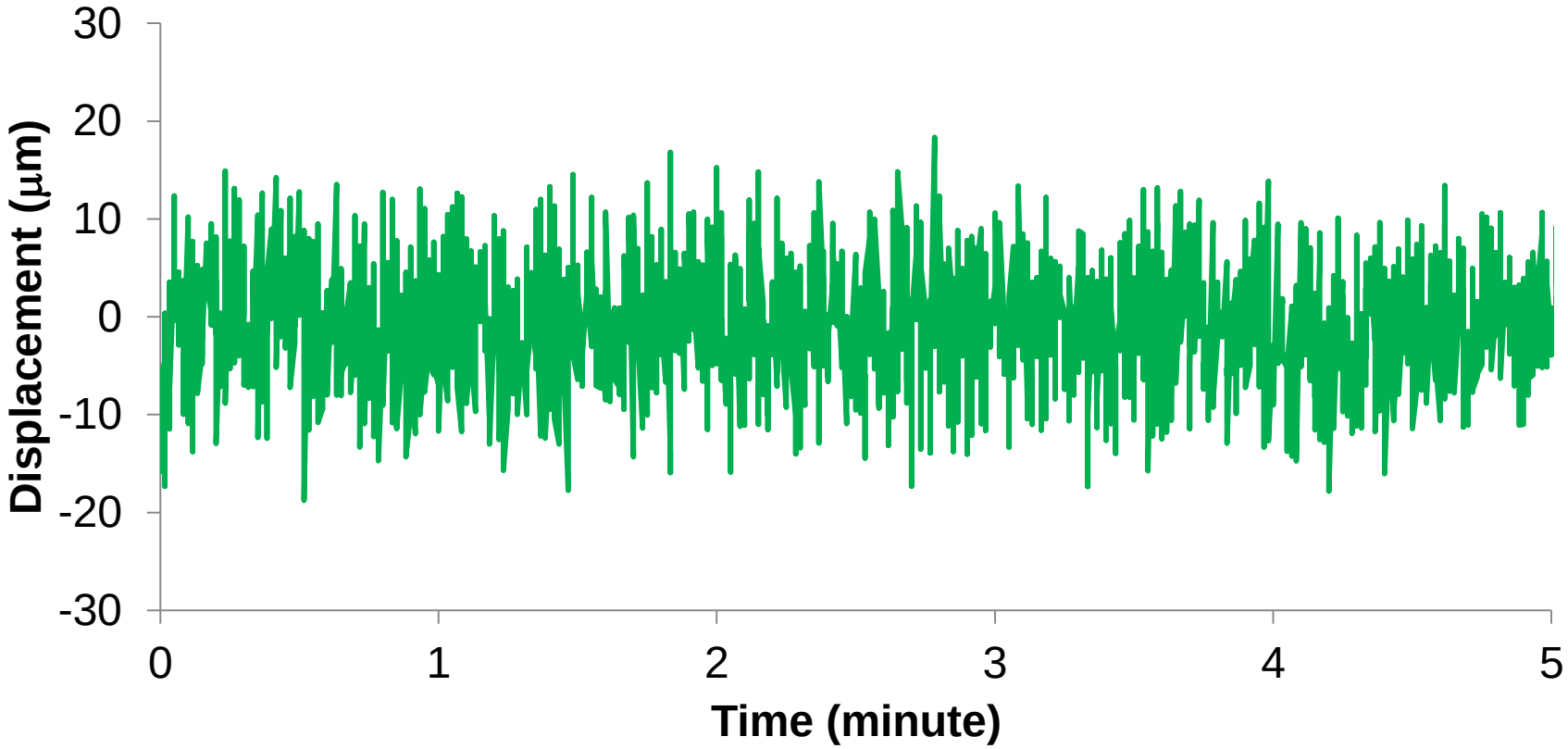
Energy stability: <10 % (pulse), <0.2 % (dose)



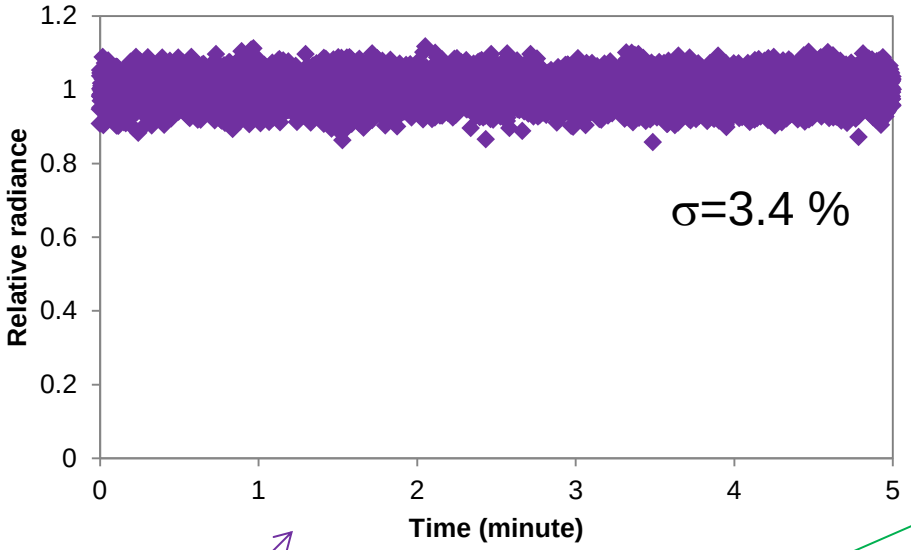


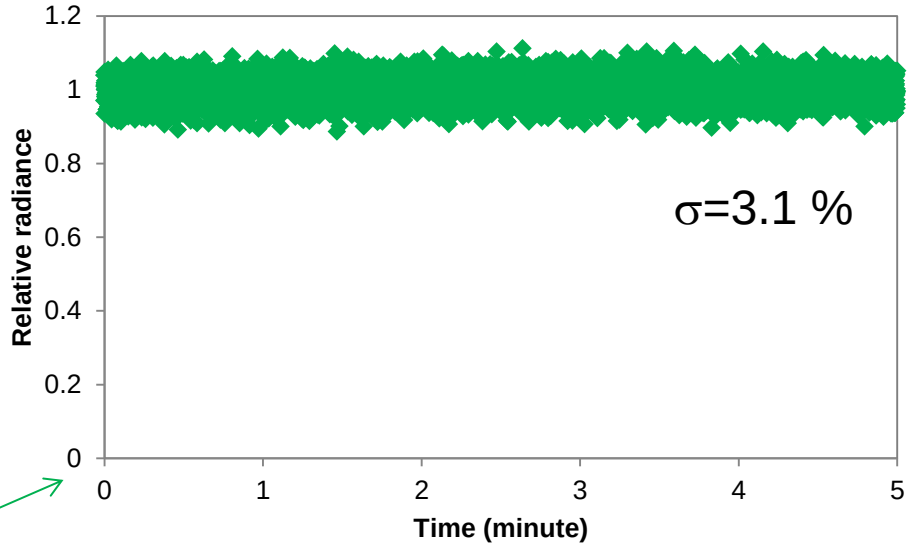
Position stability: ~6 μm

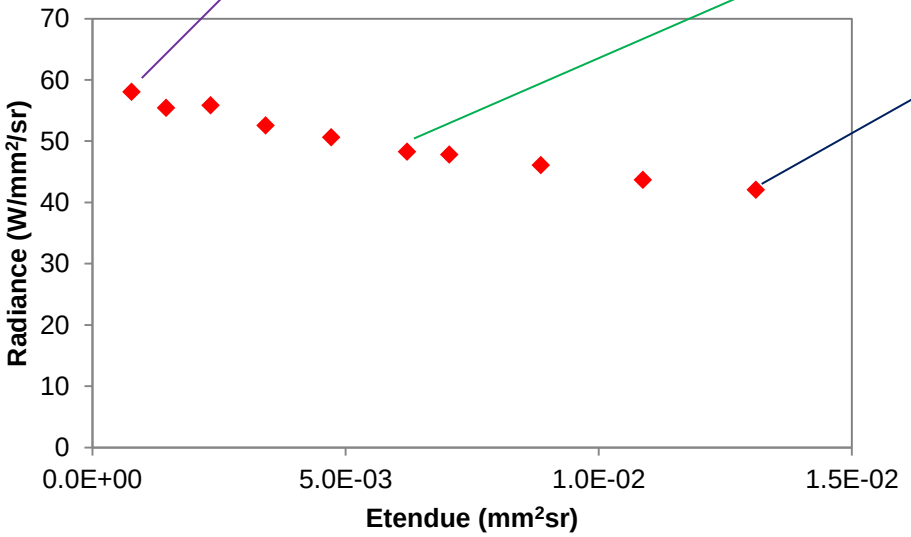
- Measured with camera placed on optical axis
  - Exposure time: 5 ms
- Standard deviation: 6.0~6.4 μm
  - <3 % of plasma size (200 μm)

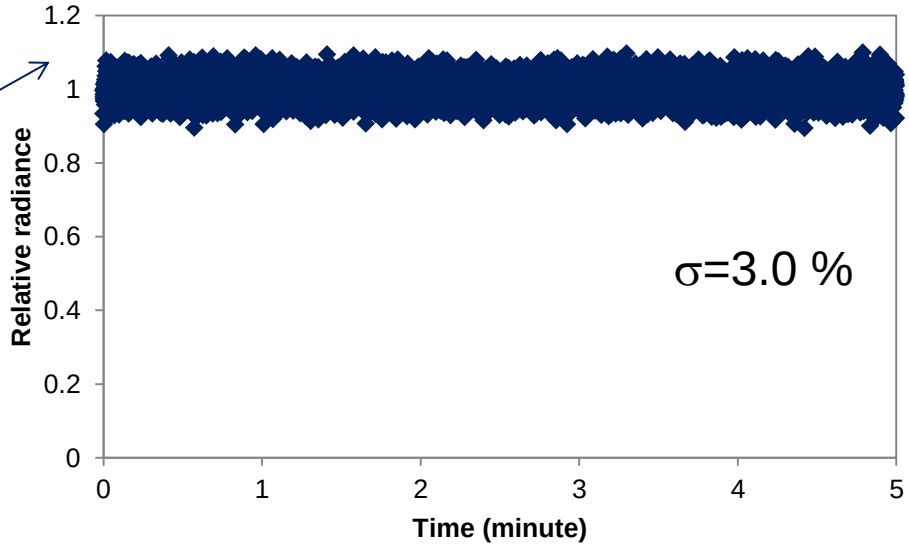


Radiance vs diameter (etendue)



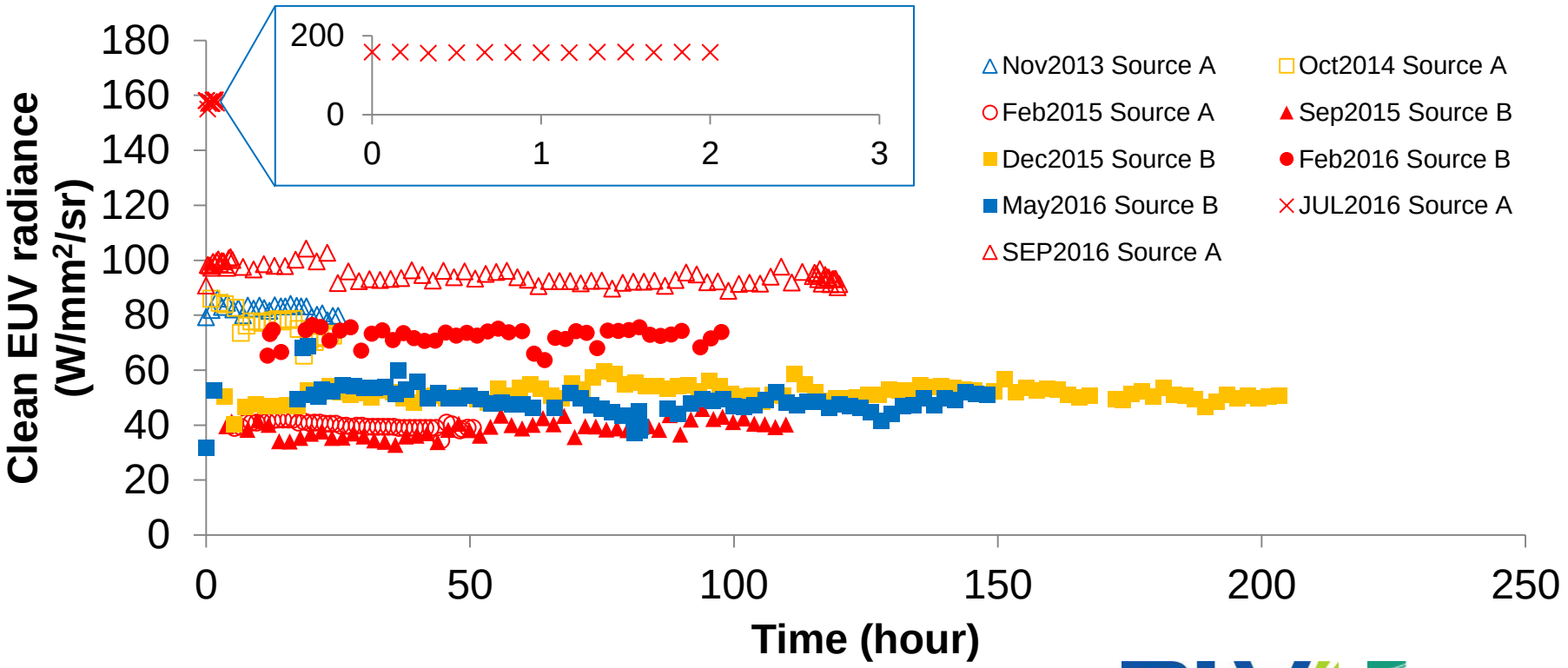






Reliability: tests ongoing

- Non-interrupted operations of up to 10 days were demonstrated, including
  - ✓ 100 W/mm^2/sr for 5 days
  - ✓ 160 W/mm^2/sr for 2 hours
- Tests continue to improve the system reliability and performance stability.



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Other applications: Compact EUV/X-ray source

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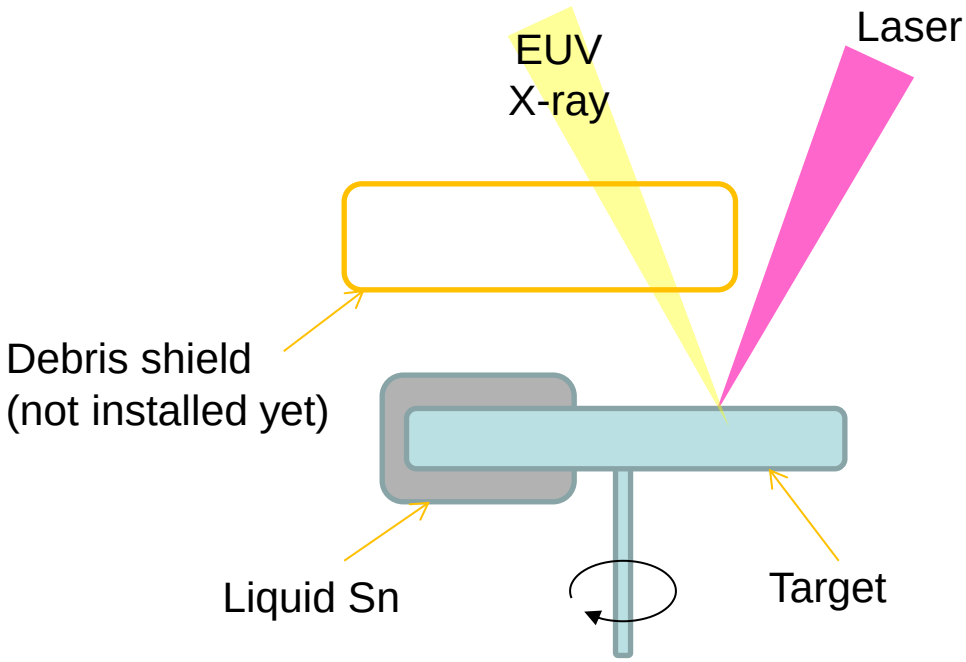
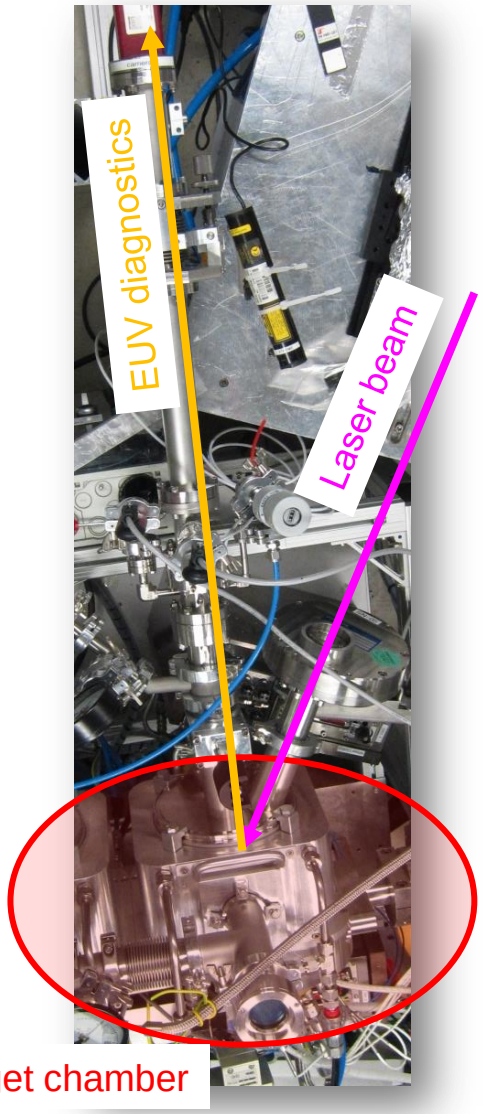
Proof-of-concept experimental setup

- Low output power
- High output radiance
- Small footprint





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Other applications: Compact EUV/X-ray source

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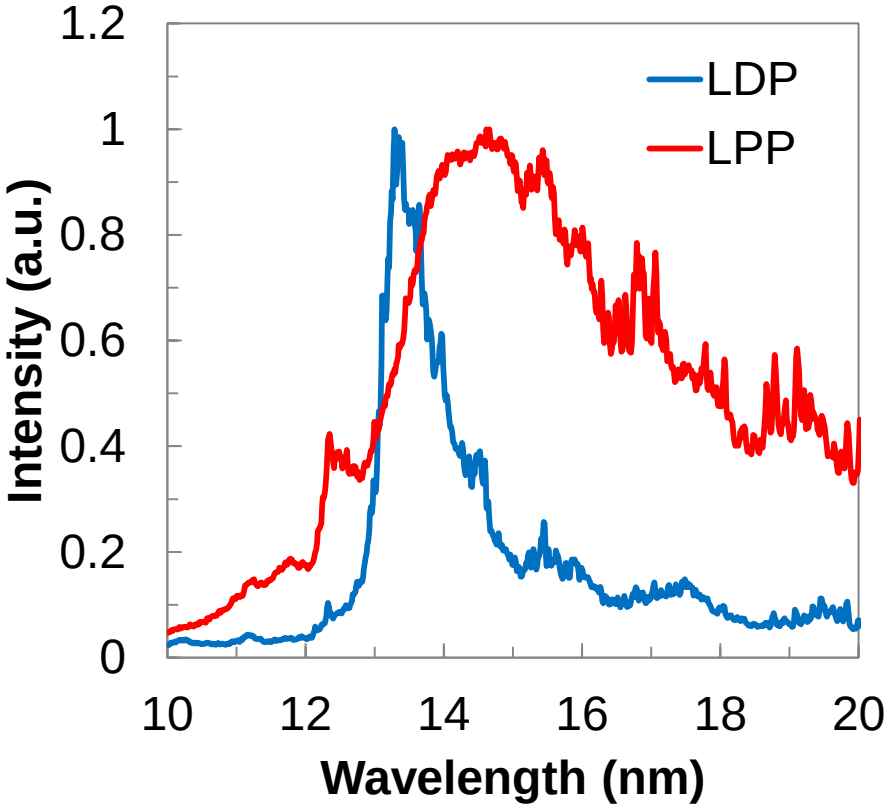
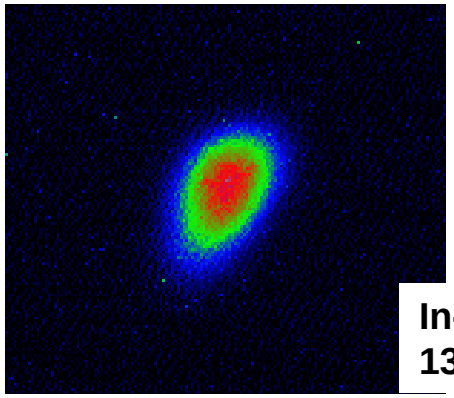
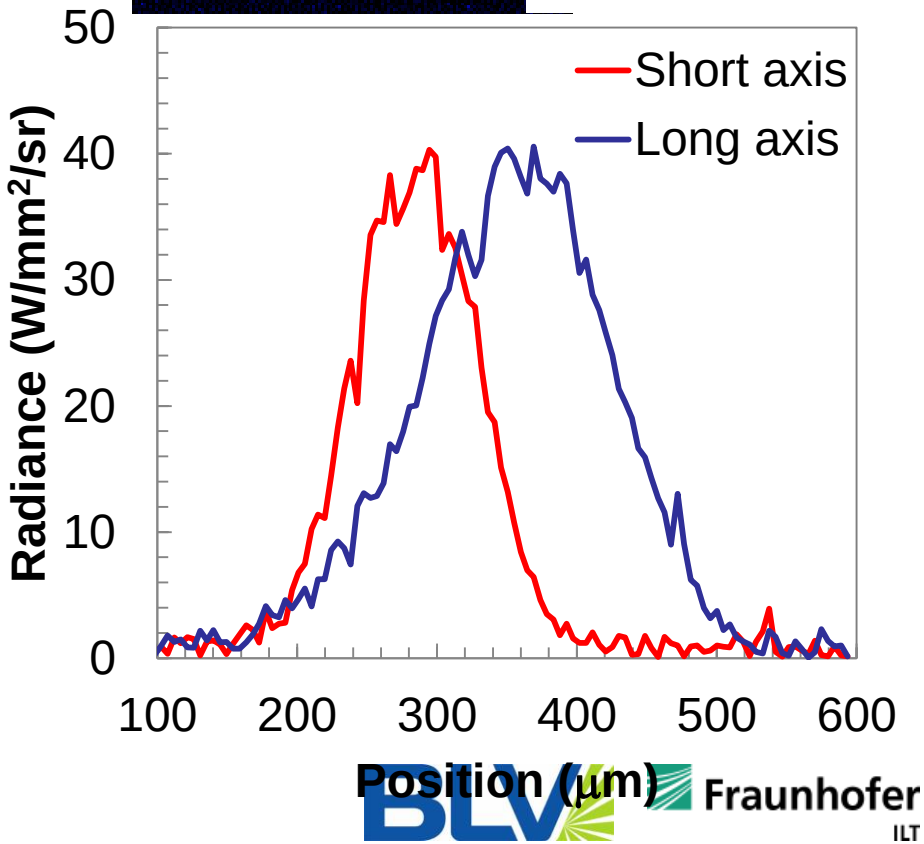
PoC exp 1





In-band EUV image
13.5 nm, 2 % BW



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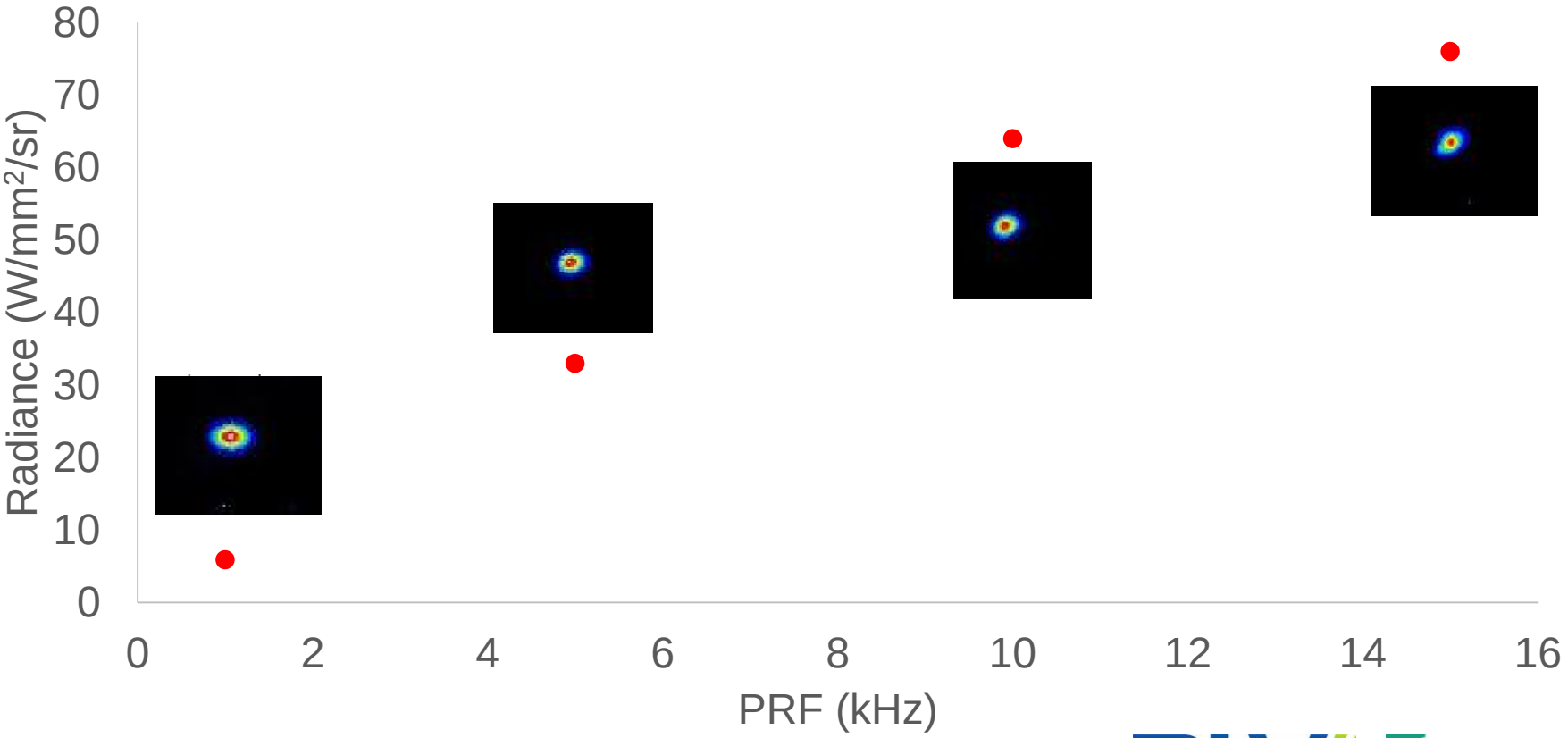
PoC exp 2

- Scalability up to 15 kHz tested. CE improvement is possible.
- Next step:
  - PoC experiment at higher frequencies.



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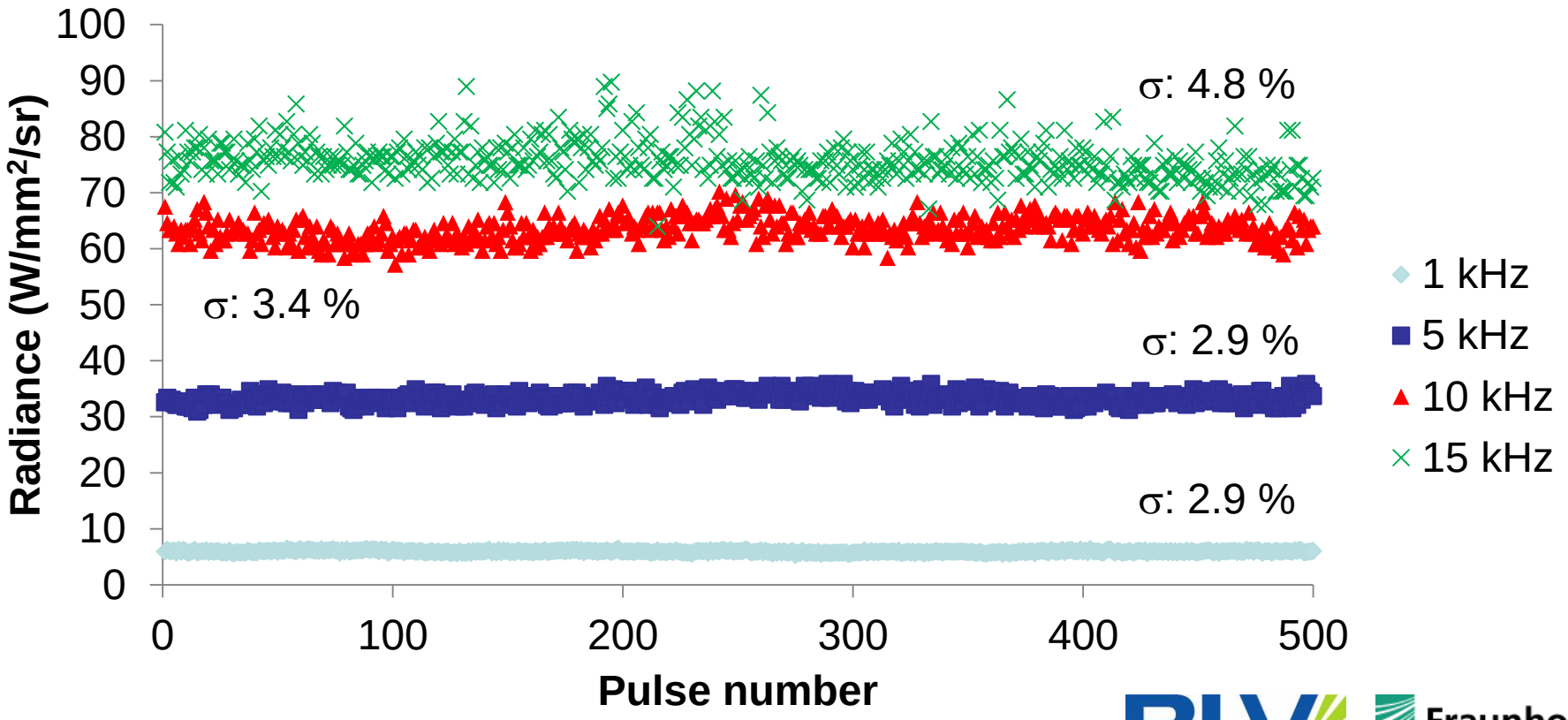
PoC exp 2

- Short-term stability was confirmed to be good.
- Next step:
  - Study on mid- and long-term stability.



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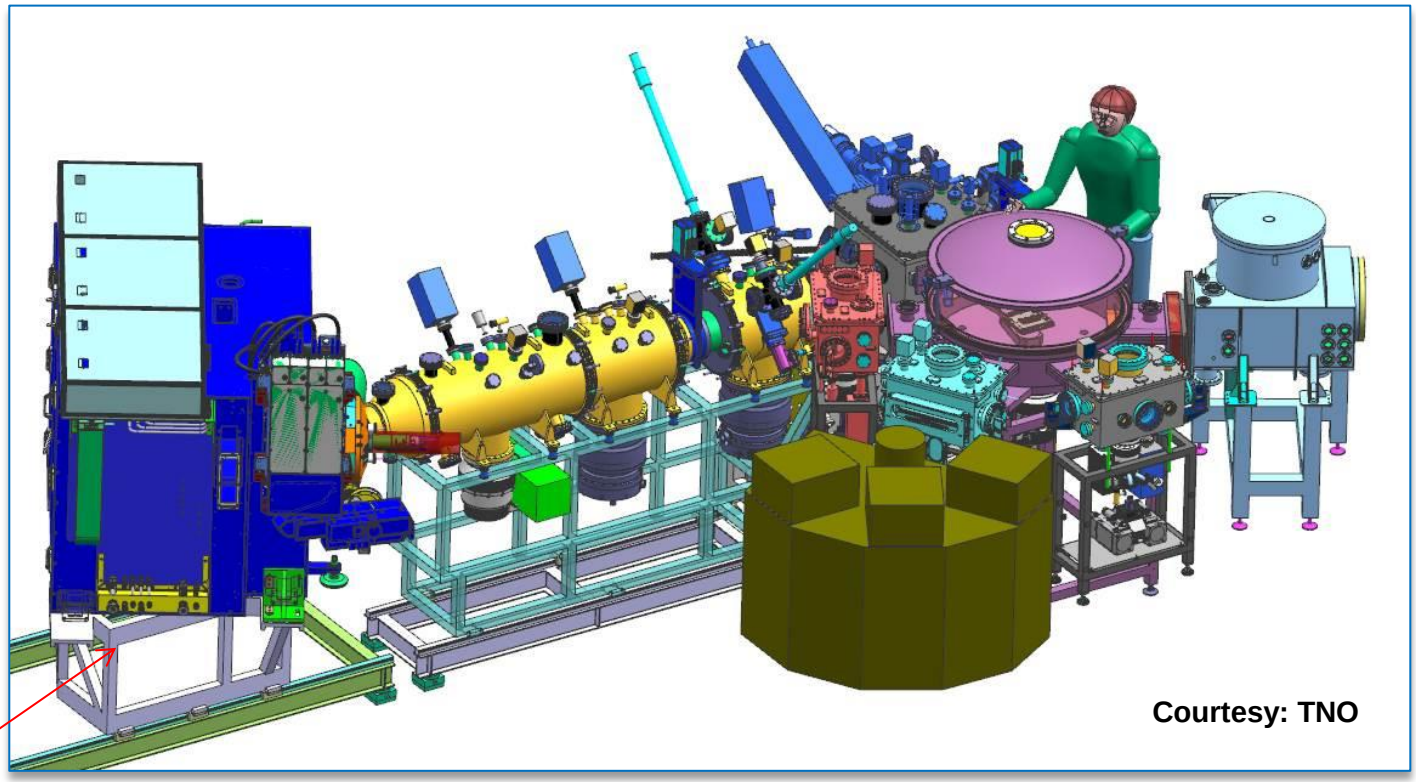
Other applications: EUV Beam Line (EBL)

An EUV source USE-3315E will be integrated to EBL2 beam line at TNO.

- Rated output power is 70 W/2πsr.
- The system is capable of up to 10 kHz.



Ushio's LDP source
"USE-3315E"

Contact: Wilbert Staring, Business Development Manager
(wilbert.staring@tno.nl)

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- Radiance of Sn-LDP source is sufficiently high for enabling EUV actinic mask inspections (ABI, API and AIMS).

- Source cleanliness has been proven.
  - No damage was observed on Mo/Si mirror samples.
- New version of the debris mitigation system was introduced.
  - Opening (collection) angle has become 2x larger than before for the future needs.

- Reliability tests are ongoing.
  - Multiple days-long tests were performed. Tests continue at higher power level.

- Preliminary experiments on the compact EUV/x-ray source are being carried out.

- An LDP source “USE-3315E” will be integrated to the EUV beam line “EBL2” at TNO in Delft, the Netherlands.

Performance summary

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Item	Performance	Remark
Pulse repetition frequency	up to 10 kHz	variable
Duty cycle	100 %	
Input power	up to 15 kW	variable
In-band EUV power	up to 300 W/2πsr	at plasma
Radiance	145 W/mm^2/sr* * value measured behind debris shield	9.5 kHz 200-μm area averaged
Plasma size	200 × 450 μm	FWHM typical value
Energy stability	Pulse: ~10 % Dose: 0.1**~3 % ** with feedback control	
Radiance stability	5.8 %*** ***from 1.5-ms-exposure observation	10 kHz
Position stability	6~10 μm	

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